"leo" or of unit mass raised through $1/g$ meters against the acceleration of gravity. Thus Prof. Bjerknes' "height" in *dynamic meters* would become the *geo-potential* in "*leo-meters*," and would differ numerically from the real height in meters only by about 2 per cent.

In this way all the objections on the score of morality or unsound terminology would be avoided, and yet the numerical value of the geo-potential in "leometers" would enable us to keep in mind a close approximation to the actual height in the consideration of the dynamic problems of the atmosphere.

It seems clear that the time has come when meteorologists may properly turn their attention to the reconsideration of their units and their nomenclature, and that the call comes with almost equal force from the theoretical, the educational, and the practical sides of their work.

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THE WINDS IN THE FREE AIR.[1]

By CHARLES J. P. CAVE, Esq., M. A., J. P., M. R. I.

[Dated April 11, 1913.]

It was noticed in very early times that the wind in the upper air may be very different from what it is on the surface. Lucretius says: "See you not, too, that clouds from contrary winds pass in contrary directions; the upper in contrary way to the lower?" Bacon advocated the use of kites in studying the winds; but it is only in quite recent years that any systematic attempt has been made to investigate the free air above the surface of the earth. Kites have been flown to a height of 4 miles, but it is a matter of some delicacy to get even as high as 2 miles.

The temperature of the free air may be recorded by a meteorograph attached to a small rubber balloon, which continues to ascend until the pressure of the gas inside bursts the envelope, and the instrument descends again to the surface. The beautiful instrument constructed by Mr. W. H. Dines, F. R. S., the pioneer of upper-air research in England, is so light that the torn fabric of the balloon is sufficient to act as a parachute and check the speed of decent.

The general result of the observations has been to show that the temperature of the air decreases with height up to a certain point, above which the temperature distribution is nearly isothermal; however much higher the balloon may ascend, there is little further change of temperature. This upper layer, discovered by M. Teisserenc de Bort, whose recent death meteorologists of every country lament, is called the stratosphere; the lower part of the atmosphere is the part that is churned up by ascending and descending convection currents and is called the troposphere. The height at which the stratosphere is reached, as well as the temperature of the layer, varies from day to day and from place to place. In England it is met with at heights varying from about 8 to 14 kilometers, with temperatures varying from $-40°$ to $-80°$ C.

It is not, however, with temperatures that I am chiefly concerned to-night, but with the wind currents in the different layers of the atmosphere. If one of the balloons carrying instruments or if a smaller pilot balloon is observed with a theodolite, its position from minute to minute can be determined, and from its trajectory or its path as it ascends the winds that it encounters can be calculated.

The theodolite used is constructed specially for the purpose; a prism in the telescope reflects the light at right angles, so that the observer is always looking in a horizontal direction, even if the balloon is overhead. It is important that the observer should be in as comfortable a position as possible, for an ascent sometimes lasts over an hour and a half, during which time the observer can only take his eye from the telescope for a few seconds at a time; otherwise he may lose sight of the balloon and be unable to find it again.

The balloon having been started from one end of the base, observations are taken from both ends at exactly the same time, usually every minute. From the positions of the balloon at each successive minute, which are plotted on a diagram, the run of the balloon during the minute can be measured, and hence the wind velocity during that minute can be obtained. After the wind velocities have been measured off and the wind directions obtained from the directions of the lines on the diagram, another diagram is constructed showing the relation of the wind velocity and direction to the height.

It is not necessary to have two observers if the rate of ascent of the balloon is known; in such a case the complete path of the balloon can be calculated from the observations of one theodolite. It is not possible to know the rate of ascent with complete accuracy, as up and down currents in the air will affect the normal rate. In practice, especially in clear weather, the method is fairly satisfactory. The method of one theodolite requires less preparation, and the subsequent calculations of the path of the balloon are less laborious than in the case of observations taken with two theodolites from opposite ends of a base line.

The best time for observations is toward sunset, so that the balloon reaches its greatest height after the sun has set on the surface of the earth. At such times the balloon, still illuminated by the sun, shines like a planet; and on one occasion I should have found it impossible to tell which was the balloon and which was Venus except for the movement of the balloon. The distances at which balloons may be seen through the telescope of the theodolite are remarkable. A striking instance was when the flash of the sun on the small meteorograph was seen—not once, but repeatedly—when the balloon was about 9 miles above the sea and at a horizontal distance of about 30 miles.

In considering the structure of the atmosphere, as it has been revealed by the observations I have carried out, principally at Ditcham on the South Downs, we may divide the subject into two parts: (A) The wind structure in the lowest kilometer and (B) the general wind distribution up to the greatest heights reached by the balloons.

It is a matter of common observation that the wind increases above the surface, and in these days of aerial navigation it is important to know the law of this increase. It seems that at Ditcham the increase in velocity is at first linear or nearly so and that the line representing the linear increase passes through zero velocity at sea level; that is to say, if we plot the wind velocity at the surface and draw through it a line from zero velocity at sea level, the wind velocities at other heights, up to half a kilometer to 1 kilometer, will lie very nearly on this line. This approximately linear increase has been found to agree with observations at several land stations, but over the sea other conditions probably prevail.

But there are occasions when this state of things does not apply at all; this is often the case in light breezes and

[1] Reprinted by permission of the author from the Proceedings of the Royal Institution of Great Britain.

at times when the surface wind is very shallow, giving place to an entirely different wind régime in the first kilometer of height. At such times it often happens that the wind velocity is greatest a very little way above the surface. The fact that there are two separate conditions emphasizes the danger of taking means. By taking the mean value of a number of separate observations we might get as a result that the wind neither increased nor decreased in the first kilometer of height, which in reality is only true on very rare occasions. As has been truly said: "La méthode des moyennes c'est le seul moyen de ne jamais connaître le vrai!"

Another question of great importance to aviators is the effect of hills upon the winds blowing over them. The balloons used in my investigations ascend at the rate of 500 feet per minute and in a few minutes are carried beyond the reach of ground eddies. In some cases, however, I have found that a balloon rose with more than its normal velocity when passing over hills if a strong wind was blowing, and the effect is visible sometimes even when the balloon is more than a kilometer above the surface; on other occasions very little effect has been observed. More light is being thrown on this question by the observations of Mr. J. S. Dines on slowly ascending balloons.

The lower layers of the atmosphere up to 1 or 2 kilometers are the most important to *aviators*. To *meteorologists* the higher layers offer problems of greater interest. In considering the winds in the free air it is convenient to have some datum to which to refer them. The observed surface wind is not convenient for this purpose, being too much affected by local conditions near the ground. A better datum is what is known as the gradient wind. Under the influence of the barometric gradient the air is being pressed toward the areas of low pressure, but the wind is actually blowing more or less along the isobars at right angles to the force. In much the same way water in a basin, when allowed to escape through a hole in the center and when given a slight movement of rotation, moves round the basin at right angles to the forces which are pressing it toward the center. In the case of the atmosphere the turning movement is given by the rotation of the earth under the moving air. For any pressure condition to be maintained the air must be moving with a certain definite velocity, depending on the shape of the isobars and the steepness of the barometric gradient. This rate can be calculated for the conditions obtaining at the time, and the wind so calculated is called the *gradient wind*. It has been found that there is a fairly good agreement between the wind so calculated and the observed wind at a height of one-half kilometer or so, but owing to friction the surface wind is usually of a smaller velocity and directed more toward the low pressure.

In order to show in a clear manner the changes of wind at different levels, I have prepared some models which give a better mental picture of the conditions than a diagram. The atmosphere is supposed to be divided up into layers, each 1 kilometer thick, and the average wind in each layer is represented by a colored card; the length of the card represents the velocity of the wind, 1 centimeter representing 1 meter per second, 1 meter per second being about 2¼ miles per hour; the direction of the card shows the direction of the wind, the arrow flying with the wind. The red cards represent winds that may be supposed to come from an equatorial direction—that is, winds from east-southeast through south to west-northwest—the blue card winds that may be supposed to come from a polar direction.

For convenience I have divided the wind structures into five types; they are perhaps rather artificial, as I shall show later, but it is convenient to make some sort of classification, even when further knowledge must change it. In the first three types of wind structure, the wind increases above the surface and equals the gradient velocity at a height of one-half kilometer or so; above this in the first class the wind remains more or less equal to the gradient velocity up to a height of 7 or 8 kilometers; in the second class the wind in the upper air greatly exceeds the gradient wind, and in the third class it falls off again to a lesser value; but in all three classes the direction remains much the same as that of the gradient wind.

The first type may be called the solid current; it does not seem to be associated with any particular type of isobars, but in a preponderance of cases the wind is easterly and the remaining cases are nearly all westerly; it is rare to find the solid current with winds from the north or from the south.

In rare cases there is hardly any wind up to the greatest heights reached, and the little wind there is often blows

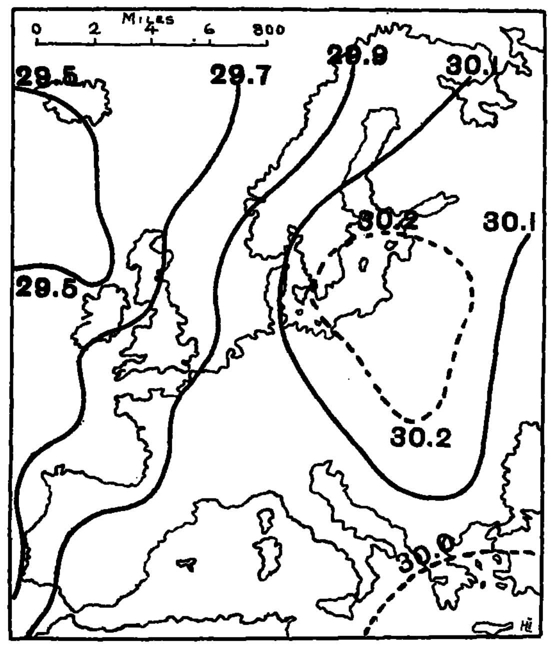

FIG. 1.—Isobars at sea level 1907, May 11, 6 p. m.

from varying directions in different layers. This type, which may be looked on as a subclass of the first type, sometimes occurs in still anticyclonic conditions in summer.

In the second class the gradient wind, after being reached at a height of about one-half kilometer, is greatly exceeded in the upper air; in some cases the wind at 2 or 3 kilometers is double the gradient value, or even more. This type is likely to occur when there is a low pressure to the north of the station and when there is a strong temperature gradient, such that the low temperatures correspond to the low pressures and vice versa. Such conditions should theoretically cause an increase in wind velocity in the upper air, but it is not possible to calculate what the effect should be without knowing the temperatures not only on the surface but in the upper air over the region in question. One may, however, calculate what effect surface temperatures would have on the isobars—at, say, 3 kilometers—assuming that the vertical temperature gradient is the same at every point. A map constructed to show the isobars which have been thus calculated must be looked on as a rough approximation only to the real conditions. A map of isobars at 3 kilometers for May 11, 1907, based on figure 1, shows how much steeper was the gradient on this day in the upper air than it was on the surface, a fact which quite accounts for the rapid increase in wind velocity from 2 meters per second at the surface to 19 meters per second at 3 kilometers.

Winds belonging to this class may come from any point of the compass.

The third class comprises those cases in which the wind, after reaching the gradient velocity in the first one-half kilometer or so, falls off more or less rapidly in the upper air. This class is almost entirely associated with easterly winds on the surface, when there is high pressure to the north and low pressure to the south. An east wind is usually, though not always, a shallow one; a southwest gale increases in the upper air, but when an easterly gale is blowing, causing such high seas and such dangers to shipping, it is curious to reflect that such a short distance up we should meet with light breezes or even a complete calm.

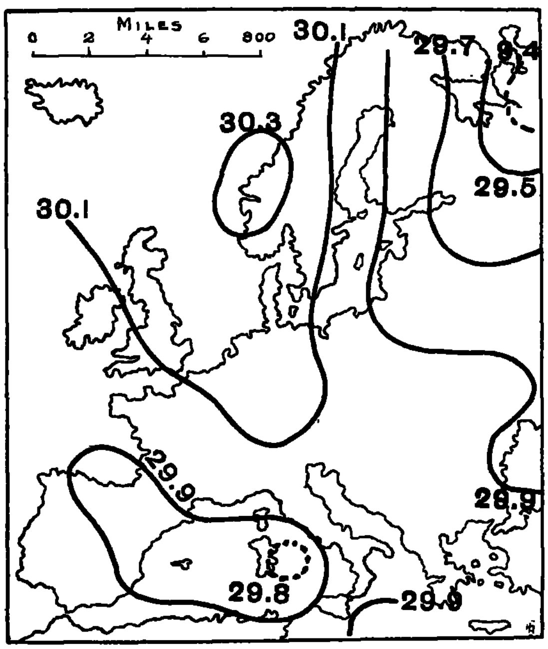

FIG. 2.—Isobars at sea level 1908, November 6, 6 p. m.

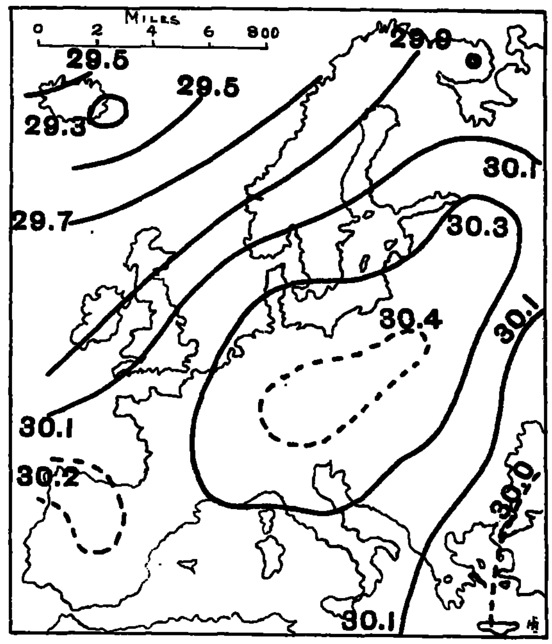

FIG. 3.—Isobars at sea level 1908, September 30, 6 p. m.

We now come to the class of reversals when the wind in the upper air is very different in direction from that near the surface, and when it often bears no relation to the surface pressure distribution. In a typical case, after an initial increase for a short distance above the surface, we find the wind gradually decreasing as we ascend, till a layer is met with, in which there is a complete calm; above this we find an entirely different wind, which usually increases as we go higher, as in the case of winds in the second class. It looks at first sight as though there were a discontinuity in the atmosphere, but I hope to show later that this is more apparent than real. A typical example of a reversal occurred on November 6, 1908 (see fig. 2), when the surface wind was easterly with a velocity of 17 meters a second, just below 1 kilometer; above this it fell off to a complete calm at 3 kilometers; at 4 kilometers there was a light northwest wind, which increased to a wind of 15 meters per second at 10 kilometers. The weather map for this day is remarkable; over this country there is no sign on the surface of the westerly wind above, but it appears that in Germany, where the pressure was highest, the westerly wind must have been descending and must have divided into two currents, one flowing on as a westerly wind over eastern Europe, the other flowing back as the easterly wind recorded in this country.

There are other cases of reversal which are not so simple as the one described above. In many cases this type is associated with small depressions or with small areas of high pressure which seem to be relatively shallow. The surface winds are related to these shallow systems, while the upper winds are controlled by larger areas of high and low pressure, shown on the weather maps at places lying farther from the point of observation.

On September 30, 1908 (see fig. 3), for instance, a southerly surface wind, after remarkable backing, gave place to a calm at 3 kilometers; above the calm another southerly wind is met with; in this case the surface wind is probably related to the high-pressure system over Germany; the upper wind to the depression approaching from the Atlantic. There was another somewhat similar case on November 16, 1908 (see fig. 4), though with winds from a different direction. The northerly surface wind backed, and a calm was met with; above this, very unexpectedly, came a thin stream of southerly wind, above which again was a north wind, increasing in velocity with height. In this case the lowest wind was part of the circulation of an anticyclone which was approaching these islands from the Atlantic. The intermediate southerly wind was perhaps the last remaining effect of the anticyclone over the Continent, while the upper wind was the outflow from above a depression near Iceland, a wind which belongs to another class to be noticed later.

In cases of reversal we find that the warm wind flows over the top of the one that comes from a colder region; there must somewhere be a line where the warm current is rising, where it must be cooled dynamically, and where its moisture may condense into cloud or rain. It is interesting to note that in most cases rain occurs somewhere in the region of the reversal, and in summer thunderstorms are frequent. Thunderclouds may often be seen to be in a wind coming from a contrary direction to the wind on the surface, and it seems possible that for anything like a sustained thunderstorm something in the nature of a reversal must exist. It is difficult to see how a difference of potential sufficient to produce lightning can be kept up unless winds from different directions are bringing masses of air at different potentials near to one another.

It has been noticed in Hampshire that when the sound of gunfiring in the Channel is distinct it is, in summer, a sign of thunder. An explanation may be hazarded: If there is a reversal so that the upper wind is coming from the south, the sound waves traveling from this point with a slight upward tendency will be refracted on entering the upper current, and thus, instead of being dissipated in the upper air, may again reach the surface at a considerable distance from their point of origin. Such conditions of wind are those productive of thunderstorms. This may also possibly account for the superstition that gunfiring produces rain. The sound of guns is only carried to great distances under the conditions I have mentioned, which are precisely the conditions favorable for heavy rains.

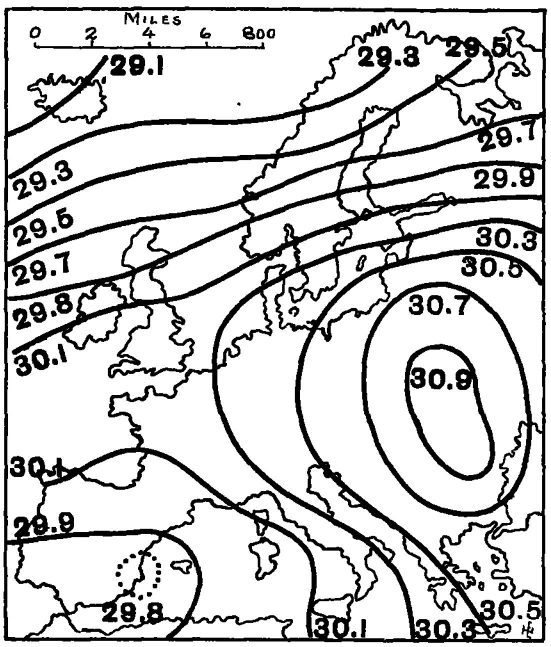

FIG. 4.—Isobars at sea level 1908, November 16, 6 p. m.

A northeast wind with rain lasting many hours is a common and a very unpleasant type of weather: it is not obvious where the moisture comes from with such a wind, for the air from the dry regions of the Continent could hardly become saturated in its short passage over the North Sea. I believe the moisture comes from the Atlantic in a southwesterly wind in the upper air. Balloons can not be followed for any length of time in such weather but I have sometimes observed that the northeasterly wind slackens considerably below the cloud level, and sometimes, when breaks in the clouds have enabled balloons to be followed a little farther, there have been unmistakable signs of reversal. A careful watch for upper clouds, seen through rifts in the lower cloud sheet, will often indicate an upper southerly wind. So sure do I feel of these facts that though living only 12 miles from the Channel I never hesitate to send up an instrument-carrying balloon in rainy weather with a northeasterly wind, feeling sure that, though the balloons may go toward the sea at first, they will ultimately return and fall on dry land. My confidence is usually rewarded, the balloons coming to earth in the midlands, or eastern counties.

The last type of wind structure to be considered is the outflow that seems to take place from the upper layers over a low-pressure system, causing west to north winds in the upper air on the east and south sides of the depression. Depressions out in the Atlantic, which cause southwest winds on the surface, give rise to west or northwest winds in the upper air over England; even cyclones as far off as Iceland produce such winds, and as they pass along the Arctic Circle, between Iceland and Norway, they show their presence by an upper northerly wind over this country. As the upper wind is often quite different from that on the surface, reversals are frequent in this class, and are associated as usual with rains and with thunderstorms in the summer. It may be that much of the rain that falls in the cyclonic depression is due to the rising of this outward flowing current over the very different surface current on the east and northeast sides of the depression.

In connection with the subject of reversals, I may mention the wave and ripple clouds that form such beautiful skyscapes. It used to be supposed that these were formed by winds from different directions flowing over one another and setting up waves; but the observations of pilot balloons have shown that between two currents from different directions there is either a layer of calm, or else the wind changes round gradually; two very different currents are not found in close juxtaposition; there is no abrupt transition between them.

To show relation of the different types of wind structure to the surface pressures, a model has been prepared; on the map are shown a depression and an area of high pressure, with arrows to show the wind directions; above the map is a sheet of glass to represent the first 5 kilometers of the atmosphere; on this are marked the winds one would expect to meet with at this level under the conditions of pressure supposed; above this sheet of glass is another representing the thickness of the atmosphere from the 5-kilometer level to the stratosphere. The model is on the scale of one-millionth, the vertical scale through the glass being approximately the same as the horizontal scale.

The churning up of the air resulting from the heating of the surface layers by contact with the earth heated daily by the sun, does not presumably reach into the stratosphere; there being no vertical movements, we should expect to find only such horizontal movements as are consistent with a suitable distribution of density. In the simplest cases the wind increases in velocity till a maximum is reached just below the stratosphere; above this the wind begins to diminish, and sometimes falls off in a very marked manner. There are occasions when all real wind seems to have ceased, and the balloon as it ascends through this curious region moves first in one direction and then in another, so that the relation of wind direction to height can only be represented on a diagram by a disconnected series of points.

What takes place still higher? Does this region of calm extend to the very confines of the atmosphere? We have practically no evidence to go on. On February 22, 1909 (see fig. 5), a meteor left a magnificent streak which was visible for two hours and a half; this trail, which was some 40 miles above the surface of the earth, moved in a manner suggesting very high wind velocities, with sudden variations in the different layers through which it passed. But it is possible that the streak of a meteor may partake of the nature of an aurora, whose luminous patches sometimes move in a remarkable way, and probably under forces other than those of the winds.

Having for purposes of classification divided the wind structure of the atmosphere into different classes, I must now attempt to put them together, and to show that some of the types that seem very different are in reality closely connected.

Following on inquiries made by Mr. W. H. Dines on the correlation between the surface pressure and various meteorological elements at a height of 9 kilometers, it was suggested by Dr. W. N. Shaw, F. R. S., that the changes of pressure to which our changes of weather are due, have their origin, not near the surface of the earth as hitherto supposed by many meteorologists, but just below the level of the stratosphere at a height of 9 kilometers or so above the surface. This view is in accordance with the observed facts of the wind distribution in the different layers of the atmosphere.

Supposing that on a certain day there is a pressure distribution just below the stratosphere, which at that level produces a westerly wind of a certain strength;

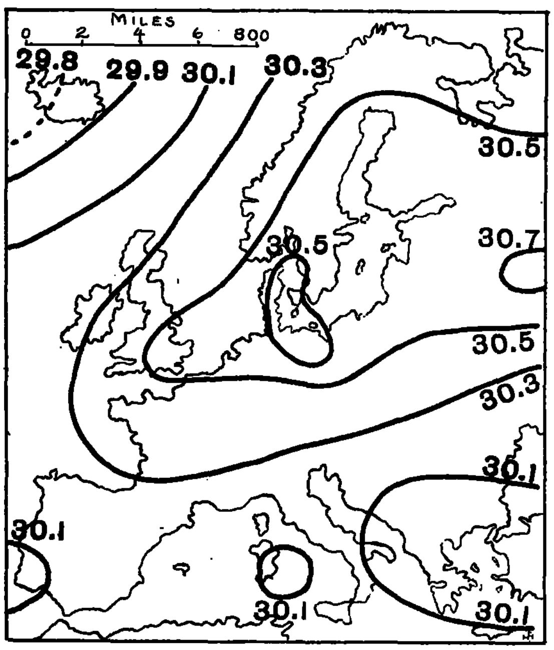

FIG. 5.—Isobars at sea level 1909, February 22, 6 p. m.

this pressure distribution will be transmitted through all the lower layers of the atmosphere, and unless modified by other conditions will produce a west wind at the surface; the velocity of this wind will, however, be only about one-third of that at the 9-kilometer level owing to the greater density of the air near the surface. If, however, the air to the north at every height were at a lower temperature than the air at a corresponding height over the place of observation, there would be at all levels a tendency for easterly winds. This will have the effect of reducing the westerly wind as we descend through the atmosphere, and when the surface is reached the west wind will have a much lower value than it would have had were it only for the increased density of the air. If the wind at the 9-kilometer level is not very strong, or if the tendency to produce an easterly wind is strong, as would be the case if the air to the north were very cold we may get a calm at the surface, or the calm may even be reached at some distance above the surface, in which case the tendency for easterly winds may actually produce such a wind which will increase in velocity as we descend toward the surface under the layer of calm and be strongest a little above the surface of the earth at a point where surface friction begins to cause a diminution of velocity.

If again at the 9-kilometer level there is a pressure distribution producing an easterly wind cold air to the north will produce a tendency for an increase of easterly wind as we descend through the atmosphere; but the greater density of the air at the lower levels will produce a decrease of wind velocity from whatever direction the wind may be coming; the two tendencies may neutralize one another in which case we get a solid current of east wind between the stratosphere and the ground level.

If there is no wind at the 9-kilometer level cold air to the north will produce easterly winds in the lower levels in which case we should find easterly winds increasing in velocity as the surface is approached.

These considerations give some idea of the mechanism by which the different types of vertical wind structure may be produced. The wind increasing with height, the solid current, the wind decreasing with height, are seen to fall into their places. The reversal, with an east wind near the surface and a west wind higher up, is only an extreme case of the slackening of the westerly wind near the surface; and the point of reversal, far from marking a point of discontinuity in the atmosphere, is seen to be merely the result of forces extending right through the lower part of the atmosphere, between the stratosphere and the earth.

If the winds are resolved into components at right angles to each other, that is north-south, and west-east components, it is found that in most cases the west-east component decreases below the stratosphere and is a minimum near the surface, an east wind in this case being considered as a negative west wind. This is what should be the case if the ideas I have been considering are correct, for the air to the north is generally colder than the air over this country. In the case of the north-south component we find no such general rule, but this also is as it should be, for the air to the east and west may be either of the same temperature, or warmer, or colder than the air over the station, in other words, there is a normal north to south temperature gradient but not a normal west to east gradient, in our islands.

The supposed cases mentioned are of course simple types, and it can be readily understood how varying conditions of pressure and temperature may in similar ways produce varieties of vertical wind distribution. In considering the pressure distribution just below the stratosphere as the regulator of the winds and the weather in the lower part of the atmosphere, I fear I have nothing to add concerning the laws governing these pressure distributions; the idea is a new one and has yet to be worked out in its details, and to stand the test of criticism and fuller investigation.

METEOROLOGY AS AN EXACT SCIENCE.[1]

By Prof. Dr. VILHELM BJERKNES.

[Delivered at the University of Leipzig, Jan. 8, 1913.]

It is a time honored custom that the newly appointed professor in his inaugural address should devote a few words to his predecessors by way of commemoration. I can not follow this example; therefore, ought I to be so much the more grateful for the honor of having been

[1] Die Meteorologie als exakte Wissenschaft. Antrittsvorlesung gehalten am 8. Januar 1913 in der Aula der Universität Leipzig. Braunschweig. 1913. 16 p. 8°.